

# **$Wh$ plus missing- $E_T$ signature from gaugino pair production at the LHC**

Howard Baer,<sup>1</sup> Vernon Barger,<sup>2</sup> Andre Lessa,<sup>3</sup> Warintorn Sreethawong,<sup>1</sup> and Xerxes Tata<sup>4</sup>

<sup>1</sup>*Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK, 73019, USA*

<sup>2</sup>*Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA*

<sup>3</sup>*Instituto de Física, Universidade de São Paulo, São Paulo - SP, Brazil*

<sup>4</sup>*Dept. of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA*

In SUSY models with heavy squarks and gaugino mass unification, the gaugino pair production reaction  $pp \rightarrow \widetilde{W}_1^\pm \widetilde{Z}_2$  dominates gluino pair production for  $m_{\widetilde{g}} \gtrsim 1$  TeV at LHC with  $\sqrt{s} = 14$  TeV (LHC14). For this mass range, the two-body decays  $\widetilde{W}_1 \rightarrow W \widetilde{Z}_1$  and  $\widetilde{Z}_2 \rightarrow h \widetilde{Z}_1$  are expected to dominate the chargino and neutralino branching fractions. By searching for  $\ell b \bar{b} + \cancel{E}_T$  events from  $\widetilde{W}_1^\pm \widetilde{Z}_2$  production, we show that LHC14 with  $100 \text{ fb}^{-1}$  of integrated luminosity becomes sensitive to chargino masses in the range  $m_{\widetilde{W}_1} \sim 450 - 550$  GeV corresponding to  $m_{\widetilde{g}} \sim 1.5 - 2$  TeV in models with gaugino mass unification. For  $10^3 \text{ fb}^{-1}$ , LHC14 is sensitive to the  $Wh$  channel for  $m_{\widetilde{W}_1} \sim 300 - 800$  GeV, corresponding to  $m_{\widetilde{g}} \sim 1 - 2.8$  TeV, which is comparable to the reach for gluino pair production followed by cascade decays. The  $Wh + \cancel{E}_T$  search channel opens up a new complementary avenue for SUSY searches at LHC, and serves to point to SUSY as the origin of any new physics discovered via multijet and multilepton +  $\cancel{E}_T$  channels

PACS numbers: 12.60.-i, 95.35.+d, 14.80.Ly, 11.30.Pb

One of the major goals of the CERN LHC is to discover or rule out as best as possible particle physics theories based on weak scale supersymmetry[1] (SUSY). Recent SUSY searches by ATLAS[2] and CMS[3] using  $pp$  collisions at  $\sqrt{s} = 7$  TeV (LHC7) have been performed in the context of the minimal supergravity (mSUGRA or CMSSM) model[4]. In this model, all scalar particles receive a common mass  $m_0$  and all gauginos acquire a common mass  $m_{1/2}$  at the grand-unified scale  $M_{GUT} \sim 2 \times 10^{16}$  GeV. Assuming the MSSM as the low energy effective theory, the various soft SUSY breaking parameters are then evolved via renormalization group equations to the weak scale, whereupon the various sparticle masses and mixings can be calculated.

Based on non-observation of signal events at rates expected beyond Standard Model backgrounds in  $\sim 1 \text{ fb}^{-1}$  of data, ATLAS and CMS have been able to plot excluded regions in the  $m_0$  vs.  $m_{1/2}$  plane of the mSUGRA model. These exclusion limits correspond to  $m_{\widetilde{g}} \gtrsim 1$  TeV in the case where  $m_{\widetilde{g}} \sim m_{\widetilde{q}}$ , and  $m_{\widetilde{g}} \gtrsim 600$  GeV in the case where  $m_{\widetilde{q}} \gg m_{\widetilde{g}}$  (the case with  $m_{\widetilde{q}} \ll m_{\widetilde{g}}$  doesn't occur in the mSUGRA model).

At the present time, ATLAS and CMS have each accumulated more than  $5 \text{ fb}^{-1}$  of data, and analyses of this data set are anxiously awaited by the particle physics community. Further running in 2012 is expected to net  $10\text{-}30 \text{ fb}^{-1}$  of integrated luminosity at  $\sqrt{s} = 7$  TeV. It is expected that LHC will be shut down during the year 2013 for upgrading, and running will resume in 2014 at a center-of-mass energy close to the LHC design value,  $\sqrt{s} \sim 14$  TeV (LHC14).

In evaluating the reach of LHC for SUSY particles, searches tend to focus on gluino pair production

( $\widetilde{g}\widetilde{g}$ ), squark pair production ( $\widetilde{q}\widetilde{q}$ ) and gluino-squark production ( $\widetilde{g}\widetilde{q}$ ), since strongly interacting sparticles are expected to be produced at the larger rates than chargino/neutralino or slepton pair production[5]. Since the gluinos and squarks are typically amongst the most massive members of the entire SUSY particle spectrum, they are expected to *cascade decay*[6] via lengthy chains into final states containing numerous jets, isolated leptons and missing transverse energy  $\cancel{E}_T$ .

To estimate the SUSY reach of any collider, first the SUSY particle masses and mixings must be calculated for a given model. Then, the various sparticle pair production reactions must be generated according to their relative probabilities (cross sections), and unstable sparticles allowed to decay using the calculated decay widths and branching fractions. Incorporation of initial and final state QCD radiation, hadronization of partons, further decays of unstable particles and a modeling of the underlying collider event will then allow for a hopefully realistic determination of what sparticle pair production events look like at the LHC.

The reach of LHC14 for  $10 \text{ fb}^{-1}$  was first evaluated in Ref. [5] for events with multi-jets +  $\cancel{E}_T$ , and later in Ref. [7] for events containing various isolated leptons plus jets +  $\cancel{E}_T$  topologies. Updated projections for  $100 \text{ fb}^{-1}$  were plotted in Ref. [8], where it was found that the LHC14 reach can extend to  $m_{\widetilde{g}} \sim 3$  TeV for  $m_{\widetilde{q}} \sim m_{\widetilde{g}}$ , while the reach is to  $m_{\widetilde{g}} \sim 1700$  GeV for  $m_{\widetilde{q}} \gg m_{\widetilde{g}}$ . The LHC7 reach was shown in Ref. [9] for integrated luminosities up to  $2 \text{ fb}^{-1}$  and later  $30 \text{ fb}^{-1}$ , while the reach for LHC14 (and LHC10) was calculated in Ref.

[10] for integrated luminosities up to 1000-3000 fb<sup>-1</sup>.<sup>1</sup> In all these studies, work was performed in the  $R$ -parity conserving mSUGRA model with the lightest neutralino  $\tilde{Z}_1$  as lightest SUSY particle (LSP).<sup>2</sup> A stable neutralino LSP provides a distinctive  $E_T$  signature at LHC, and may be associated with a dark matter WIMP.

In models with gaugino mass unification (*i.e.* the soft SUSY breaking gaugino masses  $M_1$ ,  $M_2$  and  $M_3$  unify to a common value  $m_{1/2}$  at energy scale  $Q = M_{GUT}$ ), the *weak scale* gaugino masses are expected to be (aside from 2-loop RG effects) in the ratio  $M_1 : M_2 : M_3 \sim 1 : 2 : 7$ . Then, in models where the superpotential Higgs mass  $\mu \gg M_{1,2}$ , one expects a gluino of mass  $m_{\tilde{g}} \sim M_3$ , a wino-like chargino and 2nd lightest neutralino with mass  $m_{\tilde{W}_1, \tilde{Z}_2} \sim M_2$  and a bino-like lightest neutralino with mass  $m_{\tilde{Z}_1} \sim M_1$ . If in addition one assumes heavy squarks (as are favored by the decoupling solution to the SUSY flavor and  $CP$  problems, the cosmological gravitino problem and proton decay), then for low values of  $m_{\tilde{g}} \lesssim 1$  TeV gluino pair production is expected to be the dominant SUSY cross section at LHC. However, as  $m_{\tilde{g}}$  increases, one samples parton distribution functions (PDFs) at higher values of fractional momentum  $x_F$ , and the gluino pair cross section drops sharply. Meanwhile, pair production of the much lighter wino-like and bino-like states samples PDFs at much lower  $x_F$ , and will suffer only a mild kinematic suppression. At some point, as  $m_{\tilde{g}}$  increases, production of  $\tilde{W}_1^+ \tilde{W}_1^-$  and  $\tilde{W}_1^\pm \tilde{Z}_2$  will become dominant over  $\tilde{g}\tilde{g}$  production.

To illustrate, we plot in Fig. 1 the next-to-leading-order in QCD (NLO) cross sections in  $pb$  (from Prospino[15]) for  $pp \rightarrow \tilde{g}\tilde{g}$ ,  $\tilde{W}_1^+ \tilde{W}_1^-$  and  $\tilde{W}_1^\pm \tilde{Z}_2$ , versus  $m_{\tilde{g}}$ , in a SUSY model with gaugino mass unification, but with  $m_{\tilde{q}} = m_{\tilde{\ell}} = 15$  TeV,  $\tan\beta = 10$  and  $\mu \simeq m_{\tilde{g}}$ . The dark curves are for LHC14, while light curves are for LHC7. In this case, we see that at LHC7,  $\tilde{W}_1^\pm \tilde{Z}_2$  production (dashed curves) has already become dominant for  $m_{\tilde{g}} \gtrsim 500$  GeV, while for LHC14,  $\tilde{W}_1^\pm \tilde{Z}_2$  becomes dominant for  $m_{\tilde{g}} \gtrsim 1$  TeV. As  $m_{\tilde{g}}$  increases,  $\tilde{g}\tilde{g}$  production falls quickly, and gaugino pair production becomes completely dominant. This suggests that in the case of very heavy squark masses, one may want to sample the dominant cross sections, which turn out to be gaugino pair production rather than gluino pair production.

Now let us restrict our analysis to LHC14, for which

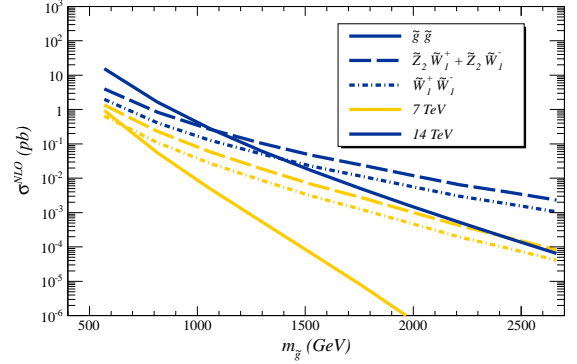


FIG. 1: Total NLO cross sections for  $\tilde{g}\tilde{g}$ ,  $\tilde{W}_1^\pm \tilde{Z}_2$  and  $\tilde{W}_1^+ \tilde{W}_1^-$  production at LHC7 (light) and LHC14 (dark), versus  $m_{\tilde{g}}$ , with  $m_{\tilde{q}} = 15$  TeV.

integrated luminosities in the 100 - 1000 fb<sup>-1</sup> range are expected. Assuming models with gaugino mass unification so that  $2M_1 \simeq M_2$  and  $\mu > M_2$ , the two-body decay  $\tilde{W}_1 \rightarrow W\tilde{Z}_1$  with  $m_{\tilde{Z}_1} \sim \frac{1}{2}m_{\tilde{W}_1}$  is expected to dominate the  $\tilde{W}_1$  branching fraction for  $m_{\tilde{W}_1} > 2M_W$ , which corresponds to  $m_{\tilde{g}} \gtrsim 560$  GeV. Likewise, the two-body decay  $\tilde{Z}_2 \rightarrow \tilde{Z}_1 h$  turns on for  $m_{\tilde{Z}_2} \gtrsim 2m_h \sim 230 - 280$  GeV, corresponding to  $m_{\tilde{g}} \gtrsim 800 - 900$  GeV. The decay  $\tilde{Z}_2 \rightarrow \tilde{Z}_1 Z$  also will occur, but usually with branching fraction  $\sim 5\%$ , compared to  $BF(\tilde{Z}_2 \rightarrow \tilde{Z}_1 h) \sim 95\%$ , for the models under consideration (since  $\tilde{Z}_1 \tilde{Z}_2 Z$  coupling only involves small higgsino components of both neutralinos, whereas the  $\tilde{Z}_1 \tilde{Z}_2 h$  coupling occurs via the higgsino component of just one of the two neutralinos). Thus, we are led to scrutinize a single production reaction followed by simple two-body decays:  $pp \rightarrow \tilde{W}_1^\pm \tilde{Z}_2 \rightarrow (W\tilde{Z}_1) + (h\tilde{Z}_1) \rightarrow (\ell\nu_\ell \tilde{Z}_1) + (b\bar{b} + \tilde{Z}_1)$ , as shown in Fig. 2. Because of potentially enormous SM backgrounds to the final state, this event topology has never been studied previously; indeed the decay  $\tilde{Z}_2 \rightarrow \tilde{Z}_1 h$  has been termed the “spoiler mode” in the literature. Here, we evaluate this signal reaction compared to SM backgrounds arising from  $t\bar{t}$ ,  $Wb\bar{b}$ ,  $WZ$ ,  $Wh$  and  $Zb\bar{b}$  production.

In our calculations, we generate particle mass spectra in the mSUGRA/CMSSM model using the Isasugra[16] spectrum calculator with  $m_0 = 5$  TeV,  $A_0 = -1.8m_0$ ,  $\tan\beta = 10$ ,  $\mu > 0$  and with  $m_t = 173.3$  GeV. We vary  $m_{\tilde{W}_1, \tilde{Z}_2}$  by varying  $m_{1/2}$ . We feed the resulting Isawig file into the HERWIG event generator[17], which maintains SUSY particle spin correlations via preprogrammed spin density matrices[18]. We normalize the signal cross section to the Prospino NLO result. We also generate  $Wh$ ,  $WZ$  and  $t\bar{t}$  backgrounds using Herwig, and

<sup>1</sup> In Ref. [10], the 100 fb<sup>-1</sup> reach of LHC14 was found to extend to  $m_{\tilde{g}} \sim 2.1$  TeV for  $m_0 \sim 3$  TeV, for  $\tan\beta = 45$ . In this region, squarks have not completely decoupled in the focus point region, so the reach is somewhat higher than expected for the squark decoupling regime ( $m_{\tilde{q}} \gtrsim 5$  TeV at LHC14).

<sup>2</sup> For LHC reach in GMSB, see Ref. [11]; for reach in AMSB, see Ref. [12] and for reach in inoMSB, see Ref. [13]; for reach in mSUGRA with hadronic RPV neutralino decays, see [14].

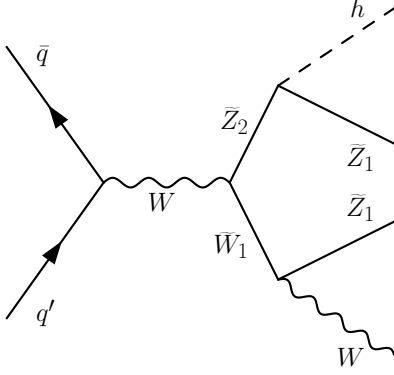


FIG. 2: Feynman diagram for  $q'\bar{q} \rightarrow \widetilde{W}_1^\pm \widetilde{Z}_2 \rightarrow (W^\pm \widetilde{Z}_1) + (h \widetilde{Z}_1)$

$Wb\bar{b}$ ,  $Zb\bar{b}$  as well as the single top<sup>3</sup> backgrounds using an AlpGEN[20]/Herwig interface. For  $t\bar{t}$  production, we use a  $k$ -factor of 2 with no  $k$ -factors for the other backgrounds. For each signal and background process, we generate a statistical sample corresponding to  $100 \text{ fb}^{-1}$  of data at LHC14.

We implement the AcerDET fast detector simulation program[21], using default ATLAS detector parameters including a cone-type jet finding algorithm with  $\Delta R(\text{jet}) = 0.4$  and  $E_T(\text{jet}) > 10 \text{ GeV}$ . A jet is tagged as a  $b$ -jet if it contains a  $b$ -quark with  $|\eta_b| < 2.5$ ,  $p_T(b) > 5 \text{ GeV}$  and the  $b$  is located within  $\Delta R < 0.2$  around the reconstructed jet axis. We also impose a  $b$ -jet reconstruction efficiency of 60%, plus a  $b$ -jet mis-tag probability on QCD jets as in Ref. [22]. We then require the following pre-selection cuts (**cuts I**):

- exactly one isolated lepton  $\ell$  ( $\ell = e$  or  $\mu$ ) with  $p_T(\ell) > 10 \text{ GeV}$  and  $|\eta(\ell)| < 2.5$ ,
- two  $b$ -jets with  $p_T(b - \text{jet}) > 50 \text{ GeV}$  and  $|\eta(b - \text{jet})| < 2$  (events with  $\geq 3$   $b$ -jets are rejected) and
- number of non- $b$ -jets with  $p_T(j) > 50 \text{ GeV}$  equals zero ( $n(j) = 0$ ).

Next, we examine a variety of distributions for a  $m_{\widetilde{W}_1} = 620 \text{ GeV}$  signal (corresponding to  $m_{1/2} = 700 \text{ GeV}$  with  $m_{\widetilde{g}} = 1800 \text{ GeV}$ ) and backgrounds, including  $\cancel{E}_T$ ,  $M_{eff} = \sum_{jets} E_T(jets) + \cancel{E}_T$ ,  $\Delta\phi(b\bar{b})$  and the transverse mass  $m_T(\ell, \cancel{E}_T)$ . In this case, the light Higgs mass is found to be  $m_h \simeq 125 \text{ GeV}$ . The SUSY signal is expected to have a much harder  $\cancel{E}_T$  and  $M_{eff}$  distribution than background, due to the large masses of the  $\widetilde{W}_1$

and  $\widetilde{Z}_2$  particles, and the presence of two  $\widetilde{Z}_1$  in the final state. In addition, since the  $\widetilde{Z}_2$  is produced typically with  $p_T(\widetilde{Z}_2) \sim m_{\widetilde{Z}_2}$ , it is expected that the  $h$  from  $\widetilde{Z}_2$  decay will be at high  $p_T$ , and give rise to more nearly collimated di- $b$ -jet cluster than background. Also, the  $m_T$  cut is expected to be very effective at cutting the bulk of the background processes, since we generally expect a Jacobian peak structure with  $m_T \lesssim M_W$  in the background, while the signal yields a continuum. We find we can gain a large background rejection while retaining much of the signal by requiring (**cuts II**):

- $\cancel{E}_T > 220 \text{ GeV}$ ,
- $M_{eff} > 350 \text{ GeV}$ ,
- $\Delta\phi(b, \bar{b}) < \pi/2$  and
- $m_T(\ell, \cancel{E}_T) > 125 \text{ GeV}$ .

In Fig. 3, we plot the di- $b$ -jet invariant mass distribution after the above set of cuts I and II. The various shaded histograms show the  $Wh$ ,  $Wh + WZ$ ,  $Wh + WZ + t\bar{t}$  and  $Wh + WZ + t\bar{t} + Wb\bar{b}$  backgrounds (single top and  $Zb\bar{b}$  events are eliminated after cut II). The unshaded histogram shows the sum of all backgrounds plus the SUSY signal for  $m_{\widetilde{W}_1} = 620 \text{ GeV}$ . From the plot, one can see the  $h \rightarrow b\bar{b}$  peak standing out beyond background, indicating a clear signal from  $\widetilde{W}_1^\pm \widetilde{Z}_2 \rightarrow Wh \widetilde{Z}_1 \widetilde{Z}_1$  production.<sup>4</sup> Both the  $h$  and  $Z$  peaks are located somewhat below their naively expected positions due to jet energy loss via radiation outside the  $\Delta R = 0.4$  cone, due to neutrino emission in the  $b$ -decays and due to calorimeter mis-measurements.

To calculate a reach for LHC14 with  $100 \text{ fb}^{-1}$ , we implement an invariant mass cut (**cut III**):

- $110 \text{ GeV} < m(b\bar{b}) < 130 \text{ GeV}$ ,

to gain a final signal sample along with background. A tabulation of signal and BG rates after cuts I, II and III is shown in Table I. We note here that the  $WZ$ ,  $Wh$  and  $t\bar{t}$  backgrounds should be very well-known due to their independent studies, and are potentially subtractable.

cuts	# of events in $100 \text{ fb}^{-1}$					
	SUSY	$t\bar{t}$	$Wb\bar{b}$	$WZ$	$Wh$	$Zb\bar{b}$
cuts I	30	612,001	12,130	709	664	669
cuts II	10	12	7	7	1	0
cuts III	6	1	1	0	0	0
						total BGs
						626,173
						27
						2

<sup>3</sup> Since our signal requires two high  $E_T$   $b$  jets we have focussed on single top production from the  $q\bar{q}' \rightarrow t\bar{b}$  (or  $\bar{t}b$ ) process with  $s$ -channel  $W$  exchange, and neglected contributions from  $gq \rightarrow t\bar{b}q'$  and the  $gb \rightarrow tW$  processes [19].

<sup>4</sup> Since the stabilization of the electroweak scale prefers sub-TeV scale third generation squarks,  $b\bar{b}l + \cancel{E}_T$  events could potentially also arise from top squark pair production although in this case the  $m_{b\bar{b}}$  distribution would not peak at  $m_h$ .

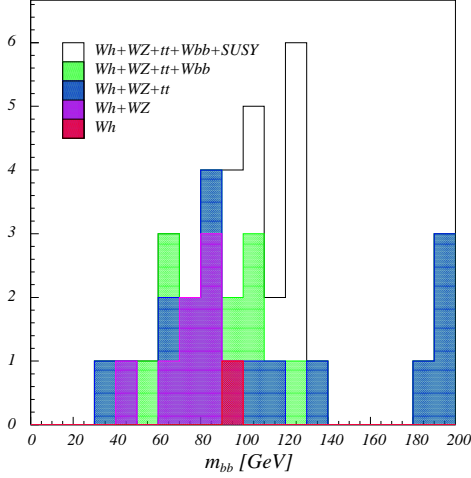


FIG. 3: Number of events expected in  $100 \text{ fb}^{-1}$  of LHC14 data versus  $m(b\bar{b})$  for various summed SM backgrounds (shaded) and SUSY signal, with  $m_{\tilde{W}_1} = 620 \text{ GeV}$  and  $m_h = 125 \text{ GeV}$ .

TABLE I: Number of events expected in  $100 \text{ fb}^{-1}$  of data at LHC14 from SUSY signal with  $m_{\tilde{W}_1} = 620 \text{ GeV}$  and from various background processes, after cuts I, II and III.

The statistical significance of the signal, evaluated using Poisson statistics, for  $100 \text{ fb}^{-1}$  (solid) and  $1000 \text{ fb}^{-1}$  (dashes) of LHC14 data with several different  $m(b\bar{b})$  bin sizes is shown in Fig. 4. Here, our signal only comes from the  $\tilde{W}_1^\pm \tilde{Z}_2$  production reaction. Other SUSY production processes would only add to these signal rates. We see that with  $100 \text{ fb}^{-1}$  of data at LHC14, a  $5\sigma$  signal emerges only for  $m_{\tilde{W}_1} \sim 450 - 550 \text{ GeV}$ . However, the  $1000 \text{ fb}^{-1}$  LHC14 reach extends across the entire mass range  $m_{\tilde{W}_1} \sim 300 - 800 \text{ GeV}$ . These results require only that weak scale gaugino masses satisfy  $M_1 \sim M_2/2$  and  $\mu > M_2$ , since we only consider  $\tilde{W}_1^\pm \tilde{Z}_2$  production. If we assume the full gaugino mass unification with  $M_3 \sim 3.5M_2$ , then the  $100 \text{ fb}^{-1}$  range of chargino masses that is accessible at better than the  $5\sigma$  level in Fig. 4 corresponds to  $m_{\tilde{g}} \sim 1.5 - 1.9 \text{ TeV}$ , while the  $1000 \text{ fb}^{-1}$  range corresponds to  $m_{\tilde{g}} \sim 1 - 2.8 \text{ TeV}$  (the range of  $m_{\tilde{g}}$  depends on variations within the SUSY model parameter space). These values turn out to be comparable to values found in Ref. [8]. The maximal SUSY reach determined in Ref. [8] and [10] were found using very hard cuts, with very low backgrounds originating from QCD processes yielding very high jet multiplicity, for which theoretical uncertainties are quite large. In contrast, the

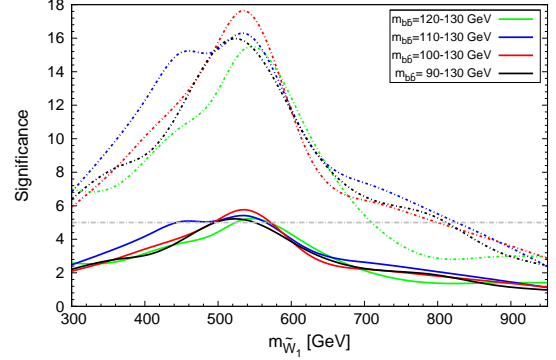


FIG. 4: Significance of signal in  $100 \text{ fb}^{-1}$  (solid) and  $1000 \text{ fb}^{-1}$  (dashes) of LHC14 data versus  $m_{\tilde{W}_1}$  for various  $m(b\bar{b})$  bin sizes. The dashed gray horizontal line shows the  $S/\sqrt{B} = 5$  significance level. We have checked that whenever the statistical significance exceeds  $5\sigma$  the signal level exceeds 5 events. We take  $m_0 = 5 \text{ TeV}$  and  $A_0 = -1.8m_0$ .

reach derived from  $\tilde{W}_1^\pm \tilde{Z}_2 \rightarrow Wh + \cancel{E}_T$  is determined using well-known QCD and electroweak background processes with lower jet multiplicities for which theoretical uncertainties should be much smaller. In addition, since our signal involves just a single  $2 \rightarrow 2$  production process followed by simple 2-body decays, the process may allow for a  $\tilde{Z}_2$  mass extraction for instance from the  $p_T(h)$  distribution if a sizable event sample can be obtained.

#### Summary:

For LHC running at  $\sqrt{s} = 14 \text{ TeV}$ , the dominant SUSY reaction for  $m_{\tilde{g}} \gtrsim 1 \text{ TeV}$  is  $pp \rightarrow \tilde{W}_1^\pm \tilde{Z}_2 \rightarrow Wh \tilde{Z}_1 \tilde{Z}_1$  in models with decoupled (heavy) scalars, gaugino mass unification and  $|\mu| > M_1, M_2$ . This reaction leads to a distinctive  $\ell b\bar{b} + \cancel{E}_T$  final state which can be detected above background levels for chargino masses of 450-550 GeV, corresponding to  $m_{\tilde{g}} \sim 1.5 - 1.9 \text{ TeV}$ , in models with gaugino mass unification, for an integrated luminosity of  $100 \text{ fb}^{-1}$ . For a  $1000 \text{ fb}^{-1}$  data sample, LHC14 should probe chargino masses in the 300-800 GeV range corresponding to  $m_{\tilde{g}} \sim 1 - 2.8 \text{ TeV}$ . This novel signal for supersymmetry from chargino-neutralino pair production not only serves to point toward SUSY as the origin of any new physics that may be discovered in the canonical multijet plus multilepton plus  $\cancel{E}_T$  channel, but potentially also increases the projected SUSY reach of LHC in models where gluinos and first generation squarks are very heavy. The simplicity of production and decay modes begs for a  $\tilde{Z}_2$  mass extraction if a sufficiently large data sample can be realized.

This work was supported in part by the U.S. Department of Energy under grant Nos. DE-FG02-04ER41305, DE-FG02-04ER41291 and DE-FG02-95ER40896 and by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP).

- 
- [1] For reviews of SUSY, see H. Baer and X. Tata, *Weak Scale Supersymmetry: From Superfields to Scattering Events*, (Cambridge University Press, 2006);
- [2] See *e.g.* G. Aad *et al.* (ATLAS collaboration), arXiv:1110.2299 (2011) and arXiv:1109.6572 (2011).
- [3] See *e.g.* S. Chatrchyan *et al.* (CMS collaboration), arXiv:1109.2352 (2011).
- [4] For a review, see *e.g.* P. Nath, hep-ph/0307123.
- [5] H. Baer, C. H. Chen, F. Paige and X. Tata, *Phys. Rev. D* **52** (1995) 2746.
- [6] H. Baer, V. Barger, D. Karatas and X. Tata, *Phys. Rev. D* **36** (1987) 96; H. Baer, R. M. Barnett, M. Drees, J. F. Gunion, H. E. Haber, D. L. Karatas and X. R. Tata, *Int. J. Mod. Phys. A* **2**, 1131 (1987); H. Baer, A. Bartl, D. Karatas, W. Majerotto and X. Tata, *Int. J. Mod. Phys. A* **4** (1989) 4111; H. Baer, X. Tata and J. Woodside, *Phys. Rev. D* **42** (1990) 1568; for earlier work on sparticle decays to just gauginos, see H. Baer, J. Ellis, G. Gelmini, D. V. Nanopoulos and X. Tata, *Phys. Lett. B* **161** (1985) 175; G. Gamberini, *Z. Physik C* **30** (1986) 605; H. Baer and E. Berger, *Phys. Rev. D* **34** (1986) 1361.
- [7] H. Baer, C. H. Chen, F. Paige and X. Tata, *Phys. Rev. D* **53** (1996) 6241; H. Baer, C. H. Chen, M. Drees, F. Paige and X. Tata, *Phys. Rev. D* **59** (1999) 055014; B. Allanach, J. Hetherington, A. Parker and B. Webber, *J. High Energy Phys.* **08** (2000) 017.
- [8] H. Baer, C. Balázs, A. Belyaev, T. Krupovnickas and X. Tata, *J. High Energy Phys.* **0306** (2003) 054; S. Abdullin and F. Charles, *Nucl. Phys. B* **547** (1999) 60; S. Abdullin *et al.* (CMS Collaboration), *J. Phys. G* **28** (2002) 469;
- [9] H. Baer, V. Barger, A. Lessa and X. Tata, *J. High Energy Phys.* **1006** (2010) 102 and arXiv:1112.3044.
- [10] H. Baer, V. Barger, A. Lessa and X. Tata, *J. High Energy Phys.* **0909** (2009) 063.
- [11] H. Baer, P. Mercadante, F. Paige, X. Tata and Y. Wang, *Phys. Lett. B* **435** (1998) 109; H. Baer, P. Mercadante, X. Tata and Y. Wang, *Phys. Rev. D* **62** (2000) 095007.
- [12] H. Baer, J. K. Mizukoshi and X. Tata, *Phys. Lett. B* **488** (2000) 367; A. J. Barr, C. G. Lester, A. Parker, B. Allanach and P. Richardson, *J. High Energy Phys.* **0303** (2003) 045.
- [13] H. Baer, A. Belyaev, T. Krupovnickas and X. Tata, *Phys. Rev. D* **65** (2002) 075024.
- [14] H. Baer, C. H. Chen and X. Tata, *Phys. Rev. D* **55** (1997) 1466.
- [15] W. Beenakker, R. Hopker, M. Spira, hep-ph/9611232 (1996).
- [16] H. Baer, C. H. Chen, R. Munroe, F. Paige and X. Tata, *Phys. Rev. D* **51** (1995) 1046; F. Paige, S. Protopopescu, H. Baer and X. Tata, hep-ph/0312045.
- [17] G. Corcella *et al.* (HERWIG collaboration), *J. High Energy Phys.* **0101** (2001) 010.
- [18] P. Richardson, *J. High Energy Phys.* **0111** (2001) 029.
- [19] T. Stelzer, Z. Sullivan and S. Willenbrock, *Phys. Rev. D* **56** (1997) 5919 and *Phys. Rev. D* **58** (1998) 094021; see also V. Barger, M. McCaskey and G. Shaughnessy, *Phys. Rev. D* **81** (2010) 034020.
- [20] M. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. Polosa, *J. High Energy Phys.* **0307** (2003) 001.
- [21] E. Richter-Was, hep-ph/0207355 (2002).
- [22] R. Kadala, P. Mercadante, J. K. Mizukoshi and X. Tata, *Eur. Phys. J. C* **56** (2008) 511.